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PERMANENT IMPACT DEFORMATION OF SPHERICAL SHELLS

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16. Abstract

Published experimental data were analyzed using dimensional analysis to obtain an empirical correlation equation for the impact deformation of spherical shells. The correlation equation obtained shows that the deformation to mean radius ratio is proportional to the square root of the shell density, to the 1.0 power of velocity, to the -0.5 power of ultimate stress, to the 0.08 power of the shell radius, and to the -0.08 power of the wall thickness. This correlation, which is based on sphere impact data obtained from shells 3/4 to 4 in. (1.91 to 10.16 cm) in diameter, was used to calculate the impact-deformation behavior of a 17-foot (5.18-m) diameter spherical containment vessel for a nuclear reactor. The predicted deformation for an impact velocity of 900 feet per second (274 m/sec) was about 7 feet (2.1 m).

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SUMMARY

Published experimental hollow-sphere impact data were analyzed to determine the effect of sphere size, material, and impact velocity on the impact deformation behavior of hollow spheres. The information was needed to predict the impact deformation of a nuclear reactor containment sphere 10 to 20 feet (3.05 to 6.10 m) in diameter for impact velocities greater than 300 feet per second (91.4 m/sec). Available data from sphere-impact experiments were for small spheres 0.750 to 4.00 inches (1.91 to 10.16 cm) in diameter and for velocities from 165 to 663 feet per second (50.3 to 202 m/sec). A method was desired of extrapolating the small-sphere data to predict the permanent impact deformation of the large sphere.

An empirical correlation of small-sphere data was obtained using dimensional analysis. The impact deflection of the surface of the sphere towards the center of the sphere was selected as the measure of the deformation of the sphere. The deformation divided by the mean radius of the sphere δ/R provided a dimensionless ratio that indicated the fraction of the sphere deformed by the impact. An empirical equation was obtained expressing δ/R as a function of the remaining dimensionless ratios.

$$\frac{\delta}{R} = 0.67\left(\frac{\rho V^2}{\sigma}\right)^{1/2}\left(\frac{R}{h}\right)^{0.08}$$

In this correlation ρ is the density of the sphere material, V is the impact velocity, σ is the ultimate stress, and h is the thickness.

The δ/R ratio was found to be directly proportional to the mean radius to thickness ratio R/h to the 0.08 power. Relatively large changes in mean radius, thickness, or in the value of the R/h ratio have only a small effect on the δ/R ratio.

Application of the correlation equation to a 17-foot (5.18-m) diameter containment vessel provided the following estimates of deformation. At an impact velocity of 300 feet per second (91.4 m/sec), δ/R is 0.28 and the deformation is 2.3 feet (0.7 m). At an impact velocity of 900 feet per second (274.3 m/sec), δ/R is 0.84 and the deformation is 7.0 feet (2.1 m).

INTRODUCTION

Safety is a primary requirement for the reactor of a nuclear airplane. Radioactive fission products must be contained within the reactor containment vessel in the event of a crash landing of the plane. The importance of safety with regard to nuclear aircraft has been discussed by Rom (ref. 1).

The proposed containment vessel is spherical, approximately 10 to 20 feet (3.05 to 6.10 m) in diameter with a relatively thin wall about 3 inches (7.6 cm) thick. This vessel must be fabricated from a material having sufficient ductility to accommodate impact deformation resulting from a crash. The shell must also have strength after impact. The high temperature gases containing fission products resulting from the afterheat and meltdown of the reactor after impact must be retained inside the sealed vessel.

Impact energy absorbers may be used around the outside surface of the containment sphere. However, if sufficient energy absorber is used to keep the sphere wall stresses below the elastic limit, the energy absorber may be too heavy (ref. 2) for an airborne system. Consequently, it may be necessary to absorb part of the energy of the impacting system by deformation of the containment vessel.

When deformation of the containment vessel is permitted, two questions arise. How much does the vessel deform during an impact? And how much deformation can be tolerated without rupturing the vessel? This report considers the first question only.

The impact of shells is a problem of relatively recent theoretical and experimental interest. The work of Young, Stoneking, and Colp (ref. 3), published in 1965, is the first available reference on the impact problem. They reported on an extensive experimental problem involving the impact of cylinders.

The first experimental work on the impact of spheres was reported by Simonis and Stoneking (ref. 4), in December 1965. They reported the results of tests of spheres 0.750 to 1.250 inches (1.91 to 3.18 cm) in diameter. Their report also included a theoretical analysis of the elastic-plastic response of spherical shells to transient loading.

Haskell (ref. 5) described the lack of agreement between the analyses and the experimental data of Simonis and Stoneking. Haskell said that the major problem with their analysis was the attempt to solve problems involving large deformations using relations based on small-deformation theory.

Haskell's contribution, reported in reference 5, is an impact failure criterion for spherical shells. He correlates his failure criterion using experimental failure velocities from the sphere tests of Simonis and Stoneking.

The maximum size sphere tested by Simonis and Stoneking was 1.25 inches (3.18 cm) in diameter. A report published by Hittman Associates, Inc. (ref. 6) includes data for 2.0- and 4.0-inch (5.08- and 10.16-cm) diameter spheres. Another report published by Hittman Associates, Inc. (ref. 7) contains data from 8.0-inch (20.32-cm) sphere tests which were conducted at Sandia Laboratories, Albuquerque, New Mexico. The Sandia test models were spherical structures containing a smaller sphere. The annulus between the two spheres was filled with a granular material. Thus the 8.0-inch (20.32-cm) diameter sphere test data could not be compared directly with the smaller sphere test data.

Haskell's empirical correlation was developed to apply the Simonis and Stoneking model test data to the design of containment vessels for nuclear power sources for use in space. His correlation is valid for the 0.750- to 1.250-inch (1.91- to 3.18-cm) range of diameters in the test data.

Application of the Haskell criterion to the impact of a very large vessel constitutes a considerable extrapolation. It was hoped that extrapolation of the criterion would provide some information about the impact failure velocity of a large (200-in. or 5.08-m diam) nuclear containment vessel. Calculation using the criterion for a vessel with a 3-inch- (7.6-cm-) thick wall gave an impact failure velocity of 0.2 foot per second (0.06 m/sec). Results of the extrapolation were not reasonable and showed that Haskell's criterion was not applicable to the design of large spheres.

A new correlation was needed to predict the deformation of the containment shell as a function of the impact velocity. This report presents an empirical correlation of published sphere-impact data (refs. 4 and 6) using dimensionless ratios obtained by dimensional analysis.

ANALYSIS

Dimensional analysis is a mathematical method useful in obtaining an orderly arrangement of the variable physical quantities involved in a problem (see Binder, ref. 8). Experimental data can provide the functional relations between the dimensionless groups obtained by dimensional analysis.

The component of the kinetic energy of the impacting sphere absorbed in the plastic deformation of the shell was assumed to be large compared with the resilient energy of the deformed shell. Consequently, elastic variables were omitted from the following list.

Symbol	Definition	Dimension
h	Wall thickness	L
R	Mean radius	L
V	Impact velocity	LT^{-1}
δ	Deformation, deflection of impact surface of sphere toward center of sphere	L
ρ	Density of sphere material	ML^{-3}
σ	Ultimate stress	$ML^{-1}T^{-2}$

The list contains six variables and three dimensions. Dimensional analysis yields the following three dimensionless π ratios.

$$\pi_1 = \frac{\delta}{h}$$

$$\pi_2 = \frac{R}{h}$$

$$\pi_3 = \frac{\rho V^2}{\sigma}$$

From this we can write the δ/h ratio as a function of the other two ratios.

$$\frac{\delta}{h} = k\left(\frac{\rho V^2}{\sigma}\right)^a \frac{R}{h}^b \tag{1}$$

Exponents a and b, and k, a constant, are to be evaluated from experimental data. The deformation can also be expressed in terms of the mean radius by multiplying equation (1) by h/R to give

$$\frac{\delta}{R} = k\left(\frac{\rho V^2}{\sigma}\right)^a \frac{R}{h}^{b-1} \tag{2}$$

The modulus of elasticity was omitted from the analysis because it is not involved in the plastic deformation of the spherical shell. Although the modulus of elasticity is involved in the resilience of the shell material on impact, the energy of resilience is assumed small compared with the portion of the kinetic energy expended in the plastic deformation of the spherical shell.

Poisson's ratio is 0.5 for materials undergoing plastic deformation. Poisson's ratio is not a variable for the plastic deformation of sphere materials and is therefore not included in the analysis.

In this analysis the stress characteristic of the impact deformation is taken as the ultimate stress obtained from static tensile tests. Better values could be obtained from dynamic stress-strain diagrams. High velocity dynamic loading tends to raise the yield strength and to increase the fracture strain (ref. 9).

Experimental sphere-impact test data were obtained from references 4, 6, 10, and 11 and listed in tables I and II. Test data were selected for those spheres that did not rupture. Rupture was determined by presence of through-the-wall cracks in the sphere.

The number of sets of sphere-impact test data was arbitrarily limited to six for those geometries for which many sets of unfailed sphere-impact test data were available. In those cases data points were selected to include the available range of impact velocity and consequently of impact energy and deformation. This limit was set to avoid having the preponderance of data from one or two sphere geometries and to obtain a better comparison of the behavior of sphere geometries for which fewer sets of data are available.

The range of impact velocity for unfailed spheres was 165 to 663 feet per second (50.3 to 202 m/sec). Mean radius to thickness ratios R/h of the sphere test data varied from 2.90 to 39.50. Outside diameters D varied from 0.750 to 4.00 inches (1.9 to 10.2 cm). Materials included SAE 4130 steel and titanium spheres tested at room temperatures, and Haynes Alloy No. 25 and Haynes Alloy No. 188 spheres tested at 1800° F (1256° K).

TABLE I. - MATERIALS DATA

Material	Yield strength		Ultimate strength		Ultimate strain	Density		Remarks
	ksi	MN/m^2	ksi	MN/m^2		lb/in.^{3}	g/cm^3	
SAE 4130	135	931	143	986	0.14	0.283	7.83	Data for 0.040 in. sheet, 1570° F (1128 K) OQ, 1000° F (811 K) - 2 hr, R_c 33 to 35 (ref. 10)
Titanium	77	531	99	683	0.20	0.163	4.51	BHN 221, as received (ref. 4)
Haynes Alloy No. 188								
Unaged	25	172	27	186	0.51	0.333	9.22	1800° F (1256 K) data (ref. 2)
Unaged	22	152	[a]34	234	.82	.333	9.22	1800° F (1256 K) data (ref. 11)
Aged	23	159	27	186	.55	.333	9.22	1800° F (1256 K) data (ref. 2) aged 500 hr at 1500° F (1089 K)
Haynes Alloy No. 25								
Unaged	27	186	27	186	0.38	0.330	9.13	1800° F (1256 K) data (ref. 2)
Aged	25	172	27	186	.32	.330	9.13	1800° F (1256 K) data (ref. 2) aged 500 hr at 1500° F (1089 K)

[a]Value used in calculations.

TABLE II. - SPHERE TEST DATA[a]

Material	Mean radius to thickness ratio, R/h	Sphere diameter, D		Wall thickness, h		Impact velocity, V		Deformation, δ	
		in.	cm	in.	cm	fps	m/sec	in.	cm
SAE 4130 Steel	2.90	0.823	2.09	0.121	0.307	337.2	103.0	0.077	0.196
						374.5	114.1	.078	.198
						311.5	94.9	.070	.178
						228.8	69.7	.045	.114
	3.25	0.750	1.91	0.100	0.254	408.2	124.4	0.097	0.246
						238.7	72.8	.041	.104
						284.1	86.6	.079	.201
						460.8	140.4	.110	.279
						480.8	146.5	.105	.267
	3.35	1.000	2.54	0.130	0.330	333.3	101.6	0.089	0.226
						363.6	110.8	.094	.239
						378.8	115.5	.095	.241
						403.2	122.9	.115	.292
						423.7	129.1	.110	.279
						257.7	78.5	.062	.157
	4.36	1.177	2.99	0.121	0.307	319.5	97.4	0.098	0.249
						331.1	100.9	.104	.264
						313.5	95.6	.099	.251
						289.9	88.4	.086	.218
						274.7	83.7	.090	.229
	4.50	1.000	2.54	0.100	0.254	176.1	53.7	0.052	0.132
						366.3	111.6	.115	.292
						543.5	165.7	.167	.424
						336.7	102.6	.105	.267
						456.6	139.2	.134	.340
						529.1	161.3	.155	.394
	4.71	0.823	2.09	0.079	0.201	176.1	53.7	0.043	0.109
						284.1	86.6	.071	.180
						418.0	127.4	.106	.269
	5.75	1.250	3.18	0.100	0.254	347.2	105.8	0.146	0.371
						317.5	96.8	.166	.422
						377.4	115.0	.165	.419
						438.6	133.7	.191	.485
	6.64	1.000	2.54	0.070	0.178	334.4	101.9	0.112	0.284
						434.8	132.5	.142	.361
						537.6	163.9	.179	.455
						662.3	201.9	.222	.564
						628.9	191.7	.216	.549
						259.1	79.0	.081	.206
Titanium	4.50	1.000	2.54	0.100	0.254	431.0	131.4	0.097	0.246
						389.1	118.6	.105	.267
						361.0	110.0	.097	.246
Haynes Alloy No. 188	19.50	2.000	5.08	0.050	0.127	368.0	112.2	0.569	1.445
						400.0	121.9	.537	1.364
	32.83	2.000	5.08	0.030	0.076	308.0	93.9	0.508	1.290
	39.50	4.00	10.16	0.050	0.127	295.0	89.9	0.859	2.182
						264.0	80.5	.889	2.258
						278.0	84.7	.984	2.499
						307.0	93.6	.917	2.329
Haynes Alloy No. 25	28.07	2.000	5.08	0.035	0.089	337.0	102.7	0.618	1.570
						165.0	50.3	.353	.897

[a]Sphere-impact test data obtained from the following references: SAE 4130 Steel and titanium sphere test data, ref. 4; Haynes Alloys No. 25 and No. 188, ref. 11.

RESULTS

Empirical correlation equations for the impact deformation of hollow spheres were obtained by evaluating the constants k, a, and b in equations (1) and (2).

Calculations were made for the dimensionless ratios. A log-log graph of δ/h against $\rho V^2/\sigma$ showed that for each geometry and material the plot of the data was essentially linear with a slope of 0.50. This slope provided the value for the exponent a in equation (1).

Each line on the graph represented values of δ/h against $\rho V^2/\sigma$ for a single sphere geometry. Readings were taken for constant values of $\rho V^2/\sigma$ from the lines drawn through each set of sphere test data points. These readings provided a set of δ/h against R/h data points which were plotted. The slope of these data points was 1.08. This slope provided the value for the exponent b in equation (1).

A plot of the deformation-thickness ratio versus the function of dimensionless ratios from equation (1) provided the value of the constant $k = 0.67$. Substitution for the unknowns in equation (1) gave the correlation equation (3).

$$\frac{\delta}{h} = 0.67\left(\frac{\rho V^2}{\sigma}\right)^{1/2}\left(\frac{R}{h}\right)^{1.08} \tag{3}$$

Figure 1 is a graph of equation (3) using the hollow sphere-impact data from reference 6. Substitution for the unknowns in equation (2) provided equation (4).

$$\frac{\delta}{R} = 0.67\left(\frac{\rho V^2}{\sigma}\right)^{1/2}\left(\frac{R}{h}\right)^{0.08} \tag{4}$$

Figure 2 is a graph of equation (4). The dashed lines in figures 1 and 2 define a range of ±30 percent for the experimental values of the deformation ratio given on the axis of ordinates.

Of the data points from 51 sphere-impact tests included in the analysis, 96 percent plotted within ±20 percent of the value for the δ/h ratio defined by the correlation line in figure 1. The fit of the data to the correlation line in figure 2 was equivalent to the fit in figure 1.

Mean radius to thickness ratios for the spheres tested varied from 2.90 to 39.50. Thus, the correlated data represented by equation (3) includes impact-deformation data for both thick-walled and for thin-walled spheres.

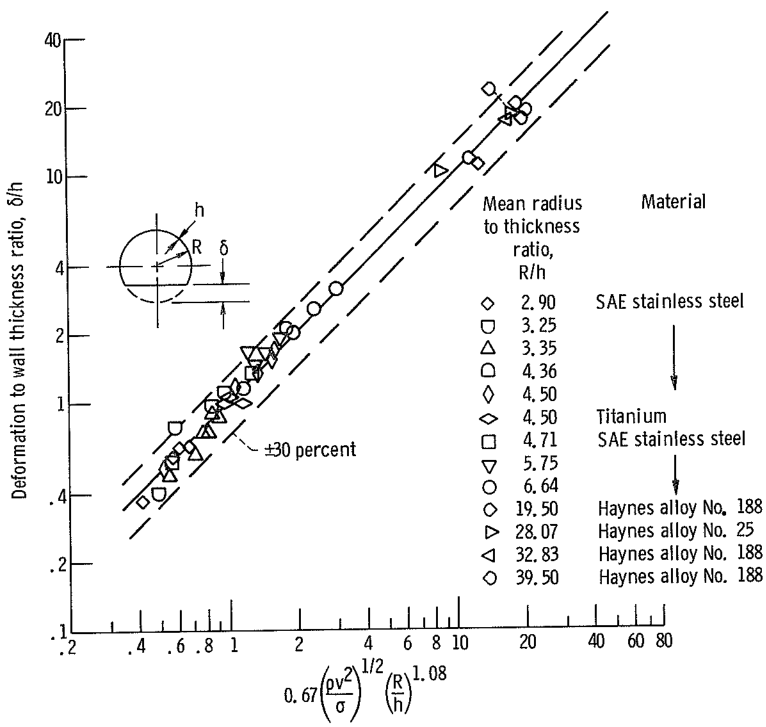

Figure 1. - Graph of correlation equation for hollow-sphere impact data.

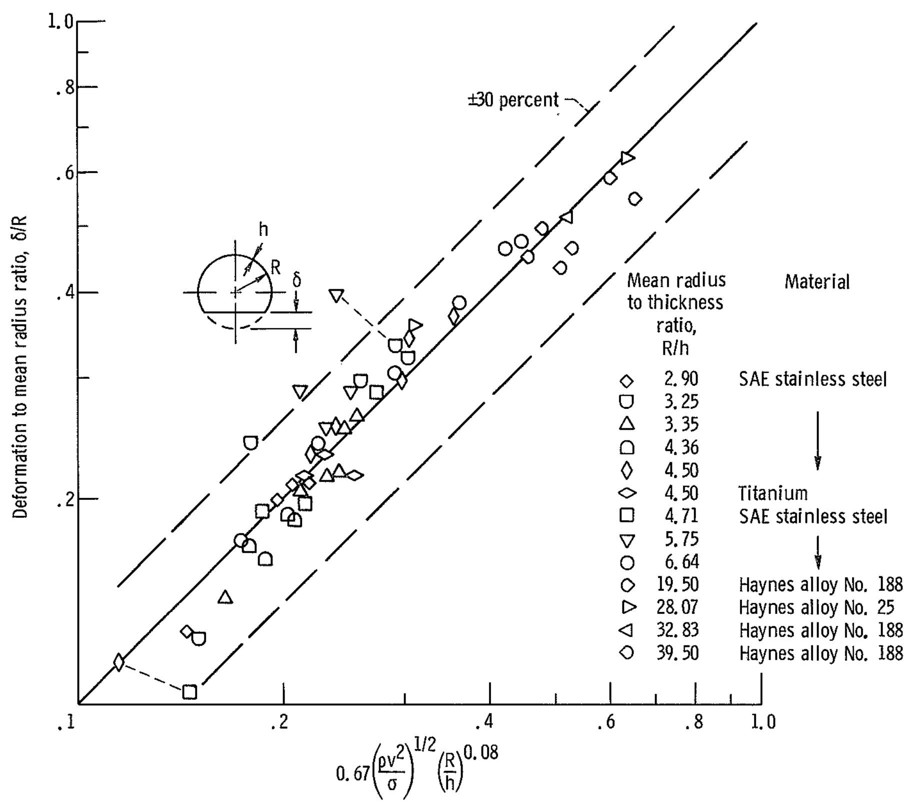

Figure 2. - Graph of deformation to mean radius ratio versus empirical correlation equation for hollow-sphere impact data.

DISCUSSION OF RESULTS

Correlation Equations

The empirical correlation equations (3) and (4) can be used to predict the permanent deflection of the surface of a hollow sphere moving normal to and impacting on a hard flat surface. These equations give the deformation of impacting spheres as a function of sphere geometry and materials properties.

Solving equation (3) for deformation δ shows that the deflection of the impact surface of the sphere is essentially proportional to the mean radius R and approximately inversely proportional to the 12th root of the wall thickness h.

The deformation is also proportional to the square root of the kinetic energy per unit volume of the sphere material and inversely proportional to the square root of the ultimate stress of the sphere material. The square root of the kinetic energy term indicates that the deformation is directly proportional to the impact velocity and to the square root of the density of the sphere material.

The equation for deformation shows that an increase in mean radius, with other parameters constant, results in a corresponding increase in the deflection of the impact surface of the sphere. If parameters other than thickness are constant, a change in thickness causes little change in the impact deformation.

The ratio of impact deformation to mean radius δ/R, is a measure of the sector of the sphere that is flattened on impact. Equation (4) reveals that the δ/R ratio is a very weak function of the R/h ratio. A 100-percent increase in the R/h ratio corresponds with less than 6 percent increase in the δ/R ratio.

The weak relation between δ/R and R/h limits the use of R/h as an impact design parameter. For example, if a value is assigned to δ/R for a given diameter containment sphere of a selected material and impacting at some velocity, then h is determined as the dependent variable. Because of the wide variation in h required to effect a small change in δ/R, the value obtained for h may be too thick or too thin. The correlation may not be valid for R/h values less than 2.9 or greater than 40 inasmuch as this is the range for which the data were correlated. By starting with the selection of R/h, and working with the other parameters in equation (4), reasonable values for variables such as deflection or velocity can be obtained. The correlation indicates that δ/R can be assumed to be independent of wall thickness. Therefore, the selection of wall thickness should be based on some other design criteria.

Dynamic Stresses

In static loading, the maximum load is applied gradually. All parts and stresses in the parts are essentially in equilibrium. In dynamic loading, the rate of change of momentum of the components must be considered. The acceleration or deceleration of parts generate dynamic loads resulting in dynamic stresses in the parts. In an impact the decelerations are high and the resulting loading and stresses are complex. The ultimate strengths of sphere materials obtained from static tensile tests were assumed to be characteristic of the dynamic stresses involved in the deformation of spheres in impact tests.

The ultimate strength was selected because dynamic stress-strain data was not available. Materials properties believed to be characteristic of the sphere impact behavior included the dynamic yield strength and the dynamic ultimate strength. The average of those two strengths would be representative of the resistance of the sphere material to deformation and rupture. The assumption that the ultimate strength was the dynamic stress important to the sphere impact tests was based on some high strain-rate tests reported in the literature.

The dynamic yield and ultimate strengths may be greater than the ultimate strengths obtained from static tensile tests (ref. 9). Hoagland (ref. 12) showed that when stainless steels were tested at higher strain rates up to 100 cm/cm/sec, plastic deformation occurred at stresses well above the static yield strength. At the fast strain-rate of 100 cm/cm/sec, he found the dynamic yield strength of 304 stainless steel to be 90 percent of the ultimate strength of the steel.

Hoggatt and Recht (ref. 13) reported that the dynamic yield strength for SAE 4130 steel heat treated to R_c 31 was 30 percent higher than the static yield strength of 122 ksi (841 MN/m^2), when specimens were loaded at strain rates of 500 to 11 000 cm/cm/sec. Weiss and Sessler (ref. 10), report that both the yield and ultimate strengths may increase under rapid dynamic loading conditions.

If the dynamic yield strength of a material reached 90 percent of the ultimate tensile strength and the ultimate strength was the same for static and dynamic loading, the average of the dynamic yield and ultimate strengths would be 95 percent of the ultimate strength. The ultimate strength would be 5 percent more than the desired average strength characteristic of the material in a sphere-impact test.

If both the dynamic yield strength and the dynamic ultimate strength were greater than strengths obtained from static tests, the average of the dynamic yield and ultimate strengths could be greater than the static ultimate strength.

Consequently, in the absence of specific information on the dynamic properties of the sphere materials, it was assumed that the average of the dynamic yield and ultimate strengths approached the ultimate static strength of the material. The ultimate strength of the sphere material was used as the dynamic stress in the correlation calculations.

Size Effects

Figure 2 provides some information on sphere geometry variations. Spheres having R/h values of 6.64, 32.83, and 39.50, with diameters of 1, 2, and 4 inches (2.54, 5.08, and 10.16 cm) fall approximately within ±10 percent of the correlation line for δ/R values near 0.5. Since a sphere with an R/h value of 6.64 is a thick-walled sphere and a sphere with an R/h value of 39.50 is a thin-walled sphere, the variation in geometry represents not only a change in diameter from 1 to 4 inches (2.54 to 10.16 cm), but also a change from thick-walled to thin-walled sphere deformation behavior.

Thick-walled spheres generally had a sector of the shell flattened upon impact. Thin-walled spheres buckled during impact deformation. The correlation line in figure 2 indicates that if a thick-walled sphere and a thin-walled sphere are tested at the same values of the abscissa function, the δ/R ratios of the impacted spheres will be the same within experimental error.

The data also shows that, for 1- and 4-inch (2.54- and 10.16-cm) diameter spheres impact tested with the same value for the abscissa function in figure 2, δ/R will be the same within experimental error; that is, a similar sector of each sphere will be deformed on impact.

The correlation equations may not be applicable outside the range of the published experimental test data used in the analysis and extrapolations should be made with caution. Applicability of the correlation equation to large diameter sphere-impact problems may be established only by large diameter sphere-impact tests.

Extrapolation

A containment sphere for a nuclear reactor is very large compared with the sizes of spheres used in the sphere-impact tests. Dimensions and parameter values for a containment sphere are given in figure 3. Calculation of velocity against deformation data for the containment sphere using the correlation equations presented in this report represents an extrapolation of a factor of 50 beyond the experimental 4-inch (10.16-cm) diameter sphere-impact test data.

The graph of δ/R against velocity in figure 3 shows that the δ/R at 300 feet per second (91.4 m/sec) is 0.28, and at 900 feet per second (274 m/sec) is 0.84. The radial deflection of the wall of the 17-foot (5.18-m) diameter containment sphere will be approximately 2.3 feet (0.71 m) at an impact velocity of 300 feet per second (91.4 m/sec) and 7.0 feet (2.1 m) at an impact velocity of 900 feet per second (274.3 m/sec).

The reliability of figure 3 depends on the important assumption that the impact-deformation of the large sphere is a function of the same variables involved in the small

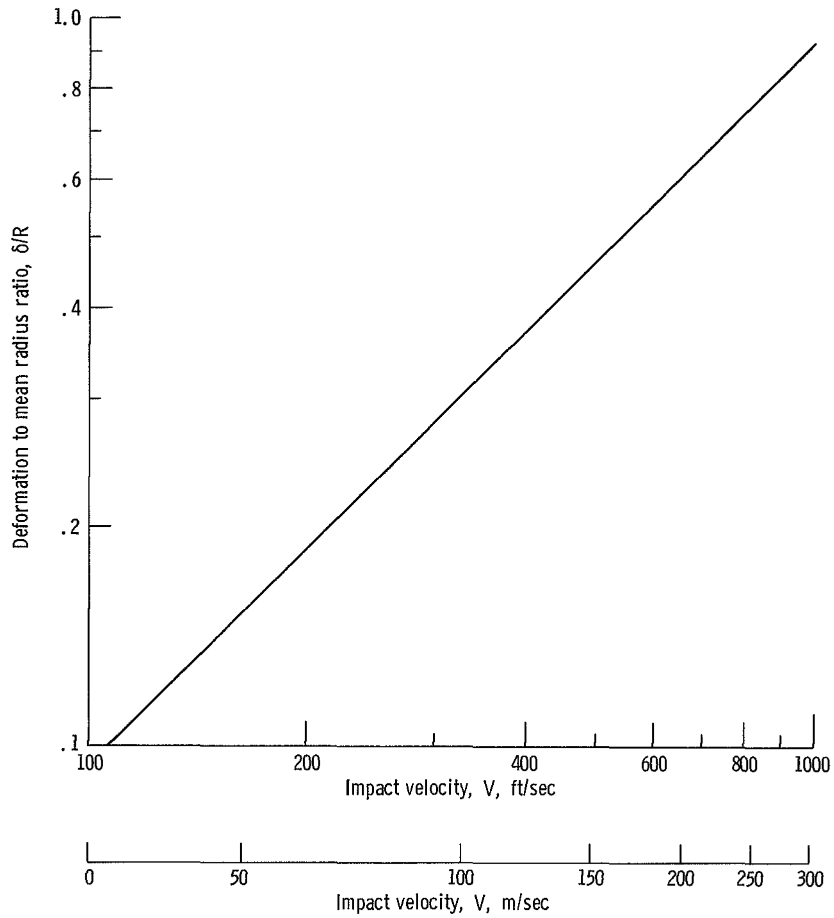

Figure 3. - Deflection to mean radius ratio versus impact velocity for 17-foot (5.18-m) diameter sphere. Thickness, 3 inches (7.62 cm); mean radius, 100.5 inch (2.55 m); mean radius to thickness ratio, 33.5; sphere material density, 0.290 pound per cubic inch (8.03 g/cm^3); ultimate stress, 100 ksi (689.5 MN/m^2); material, AISI 304 stainless steel.

sphere-impact correlation. That assumption implies that no new variables are involved in the impact deformation of the large sphere. Data from large sphere-impact tests are needed to expand the range of application of the correlation equation and to improve the reliability of predicting the impact-deformation of large spherical containment shells.

SUMMARY OF RESULTS

The following conclusions are based on analysis of published sphere-impact test data for small hollow spheres that survived impact. The range of the data is as follows: The impact velocity varied from 165 to 663 feet per second (50.3 to 202 m/sec). Sphere geometries covered a range from thick-walled to thin-walled spheres. Mean radius to thickness ratios of the sphere test data varied from 2.90 to 39.50. Outside diameters varied from 0.750 to 4.00 inches (1.91 to 10.16 cm). Materials included SAE 4130 steel and titanium spheres tested at room temperature, and Haynes Alloy No. 25 and Haynes Alloy No. 188 spheres tested at 1800° F (1256 K).

1. Empirical correlation equations given in the report can be used to predict the permanent deflection of the surface of a sphere moving normal to and impacting on a hard flat surface.

2. Thin-walled and thick-walled sphere-impact data correlated with a single equation.

3. The deflection of the impact surface of a sphere is directly proportional to the square root of the kinetic energy per unit volume of sphere material. Hence, the deflection is directly proportional to the impact velocity and to the square root of the density of the sphere material.

4. The deflection of the impact surface of a sphere is inversely proportional to the square root of the ultimate stress of the sphere material.

5. The impact deflection of a sphere is approximately proportional to the mean radius and inversely proportional to the 12th root of the thickness of the spherical shell or is almost independent of shell thickness.

6. A large change in the mean radius to thickness ratio has a small effect on the deflection to radius ratio.

7. Extrapolation of the correlation equation indicated that a 17-foot (5.18-m) diameter containment vessel would deflect approximately 7.1 feet (2.1 m) for an impact velocity of 900 feet per second (274.3 m).

8. Information obtained by extrapolation of the correlation should be used with caution since the equations may not be applicable outside the ranges of the parameters in the experimental test data used in the analysis.

9. Impact deformation tests of large diameter spheres are needed to determine size effects on the impact-deformation of spheres several feet in diameter compared with the behavior of the small-diameter spheres for which experimental test data are available.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 23, 1970,
126-15.

REFERENCES

1. Rom, F. E.: Status of the Nuclear Powered Airplane. J. Aircraft, vol. 7, no. 4, July-Aug. 1970.
2. Puthoff, Richard L.; and Gumto, Klaus H.: Parametric Study of a Frangible-Tube Energy-Absorption System for Protection of a Nuclear Aircraft Reactor. NASA TN D-5730, 1970.
3. Young, C. W.; Stoneking, C. E.; and Colp, J. L.: Containment Capsule Impact Safety Study, Phase A, Progress Report. Rep. SC-RR-65-9, Sandia Corp., July 1965.
4. Simonis, John C.; and Stoneking, Charles E.: A Study of Impact Effects of Spherical Shells. Part II. A Theoretical and Experimental Study of the Response of Spherical Shells to Impact Loads. Rep. SC-CR-67-2540, Sandia Corp., Dec. 1966.
5. Haskell, Donald F.: Impact Failure Criterion for Cylindrical and Spherical Shells. Shock and Vibration Bulletin, no. 39, part 5, Naval Research Lab., 1968, pp. 21-27.
6. Anon.: Spherical Capsule Technology Program, Heat Source Technical Report. Rep. HIT-370, Hittman Assoc., Jan. 1969.
7. Anon.: Spherical Capsule Technology Program, Addendum to the Heat Source Technical Report. Rep. HIT-412, Hittman Assoc., July 1969.
8. Binder, R. C.: Fluid Mechanics. Prentice-Hall, Inc., 1947, Ch. 6.
9. Faupel, Joseph H.: Engineering Design. John Wiley & Sons, Inc., 1964, Ch. 9.
10. Weiss, V.; and Sessler, J. G., eds.: Aerospace Structural Metals Handbook. Vol. I: Ferrous Alloys. Syracuse Univ. Press, 1963, Code 1201.
11. Anon.: Haynes Developmental Alloy No. 188. Publ. No. F-30, 361, Union Carbide Corp., Materials Systems Div., Aug. 1967.
12. Hoagland, R. G.: Effect of Strain Rate on Mechanical Properties of Austenitic Stainless Steels. Rep. BNWL-1105, Battelle Northwest Lab., Sept. 1969.
13. Hoggatt, C. R.; and Recht, R. F.: Dynamic Stress-Strain Relationships Determined from Expanding Ring Experiments. Presented at the Second International Conference of the Center for High Energy Forming, Estes Park, Colo., June 23-27, 1969.

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